

The University of Chicago

THE MECHANICAL ANALYSIS OF
RELATED SAMPLES OF
GLACIAL TILLS

- I. THE MECHANICAL ANALYSIS OF FINE-GRAINED
SEDIMENTS
- II. TEXTURAL AND LITHOLOGICAL VARIATIONS IN
GLACIAL TILL

A PART OF A DISSERTATION SUBMITTED TO
THE FACULTY OF THE DIVISION OF THE
PHYSICAL SCIENCES IN CANDIDACY FOR
THE DEGREE OF DOCTOR OF PHILOSOPHY

DEPARTMENT OF GEOLOGY AND PALEONTOLOGY

1932

By
WILLIAM C. KRUMBEIN

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THE MECHANICAL ANALYSIS OF FINE-GRAINED SEDIMENTS¹

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ABSTRACT

Older methods of mechanical analysis are briefly discussed and contrasted with the newer precision methods. The pipette method is chosen from the latter as one based on sound principles and yet simple in operation. The principles of the method, its range of application, and inherent sources of error are taken up. A standardized routine for the preparation of samples for analysis is described, and a comparison is made of the pipette method with one of the older routine methods. A flow sheet, indicating in graphic form the steps involved in analyzing a sediment, is appended.

INTRODUCTION

Among the methods which have been used for the mechanical analysis of fine-grained sediments are two which have been most widely applied by sedimentary petrologists. These are the decantation or sedimentation method, and rising current elutriation. There are certain disadvantages to both of these methods, which have long been recognized. The decantation method suffers from the difficulty of obtaining a complete separation of the finer material from any grade size, and the long settling-periods and large number of decantations necessary among the smaller ranges introduces a serious element of tediousness. Rising current elutriation, while eminently suitable for the silt sizes above the limit where flocculation is effective, suffers also from the practical impossibility of separating very fine grades by its means. Neither of these methods is suitable for material

much below 0.01 mm. in diameter, and in the case of sediments whose particles lie wholly below this diameter, they are valueless.

In recent years soil scientists have perfected numerous devices for the determination of the finer components of soils, many of which are equally applicable to sediments. These newer precision methods differ from the older techniques in at least one striking manner; the older methods endeavored to separate the various grades as units, while the newer ones do not. This modern approach to the problem was first made by Odén in 1915, when he showed that the size distribution of soils could be determined from a curve based on the weight of sediment accumulating at the base of a column of suspension, as a function of the time. For the practical application of the method he devised his continuous sedimentation balance. In 1918 Wiegner developed a continuous sedimentation cylinder in which the hydrostatic pressure at a fixed point

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below the surface of the suspension was measured as a function of the time, and the curve so obtained served in a manner similar to Odén's curves as a means of determining the size distribution. Numerous other devices based on measurements of hydrostatic pressure or of density at some point in the suspension have been advanced since. A review of these developments has recently been published by the writer.²

THE PIPETTE METHOD

The apparatus used in many of the newer techniques is quite expensive, and a precision method embodying the soundness of principle of the others, but having the advantage of low cost and simplicity of operation, would be preferable to a majority of workers. Fortunately, such a method has been introduced in recent years. It is the pipette method established independently in 1922 by Robinson in England, Krauss in Germany, and Jennings, Thomas, and Gardner in America. In its bare essentials the method consists of preparing a suspension of known concentration, and permitting it to rest until all particles greater than a given size have settled 10 cm. below the surface. The suspension is then sampled at this level with a 10- or 20-cc. pipette, and the sample dried and weighed. The suspension is shaken again, and allowed to rest until the next smaller sized particles have settled 10 cm. below the surface. Another pipette sample is withdrawn, and the weight of the dried residue determined. By subtracting the weight of the second residue from that

of the first, the amount of material in the intermediate grade is found. A multiplying factor, based on the proportion of the pipette to the total volume, converts the results into terms of the total sample.

The principles upon which this method is based have been discussed by its originators, but a brief summary may not be amiss here. It rests upon the assumption that in a dilute suspension the particles settle as individuals, an assumption which is inherent in any method of analysis. If a suspension is thoroughly shaken so that the particles are uniformly distributed, and then set at rest, all particles having a settling velocity greater than h/t will have settled below a plane of depth h below the surface, at the end of an interval of time t . All particles having a velocity less than h/t , however, will remain in their original concentration at depth h , because they will have settled only a fraction of this distance in time t . If a small sample is taken from this depth at time t , and evaporated to dryness, the weight of the residue will represent the total amount of material having settling velocities less than h/t , after the weight of the residue is multiplied by a factor based on the proportion of the sample to the total volume of suspension.

After the first sample has been taken, the suspension is shaken again, and a greater period of time is allowed to elapse, so that particles of a next smaller size may settle below depth h . The second pipette sample will then contain a residue smaller than that of the first sample by an amount equal to the weight of material lying between the

² This *Journal*, vol. 2, pp. 89-124, 1932.

two chosen velocities. The process may obviously be repeated, and by simply subtracting the weights of successive residues, the amount of material in any grade may be determined directly.

In order to translate settling velocities into radii, recourse may be had to Stokes' law, in which $v = Cr^2$, where C is a constant under any given set of conditions. The constant may be evaluated for a standard set of conditions, and the only requisite is then that all analyses be run under these same circumstances. The writer has evaluated the constant for 20°C., assuming an average specific gravity of the sediment equal to 2.65. With these limiting conditions the value of the constant is 3.57×10^4 , and by multiplying the square of the radius in cm. by this constant, the settling velocities in centimeters per second are obtained. The velocities are then converted into hours, minutes, and seconds required for a particle to settle a depth of 10 cm., by using the formula $v = h/t$. In practice it is convenient to use a single computation, where $t = h/Cr^2$.

It is obvious that the radii determined by Stokes' law are in terms of spheres,

and in order to correct for the effects of non-spherical shapes, many writers have proposed various additive factors, or have simply ignored Stokes' law, and used average hydraulic values to represent given radii. In order to obtain some standardization, and to allow comparisons to be made, the writer would like to suggest the adoption of Odén's "equivalent radius," in which the settling velocity of any shaped particle is expressed in terms of the radius of a sphere having the same settling velocity. This appears to be a logical solution of the difficulty, because it furnishes a standard basis for reporting analyses, and yet permits individual workers to add such corrective factors as they wish to the basic data obtained. Such a concept as that of the equivalent radius is not a radical departure, because even in the sieving of sediments the shapes of particles determine in part their distribution, and an implied acceptance of an "equivalent radius" is universal among workers. It seems eminently desirable, therefore, that a similar concept be adopted for grades separated by their settling velocities.

TABLE SHOWING TIME REQUIRED FOR PARTICLES TO SETTLE H CENTIMETERS, ON BASIS OF PRINCIPLE OF EQUIVALENT RADIUS*

Diameter in mm.	Velocity in cm./sec.	H in cm.	Hrs.	Min.	Sec.
1/32	0.08688	10	0	1	55
1/64	0.02172	10	0	7	40
1/128	0.00543	10	0	30	40
1/256	0.001357	10	2	2	40
1/512	0.000339	10	8	10	40
1/1024	0.0000847	5	16	21	20
1/2048	0.00002117	5	49	25	20
1/10,000	0.000000892	5	1560	36	0

* The values in the table are based on a temperature of 20°C., and an average specific gravity of the sediments equal to 2.65.

On the basis of an equivalent radius, the writer has computed the necessary values for the pipette method in terms of the generally-adopted Wentworth grade-scale. These values are shown in the accompanying table, which presents the diameter of the particle, the settling velocity according to Stokes' law, and the time in hours, minutes, and seconds for the particle to settle a given depth under the assumptions that the temperature is 20°C., and the average specific gravity 2.65. It will be noted that the first several values are computed to a depth of 10 cm., and the last several to a depth of 5 cm. This change in the depth of sampling was made in order to reduce the time of settling to a more reasonable figure.

The values given in the table range from diameters of 1/32 mm. to 1/10,000 mm. The choice of these limits was governed by the limits of applicability of Stokes' law. According to Gessner;³ the upper limit of validity of Stokes' law is a diameter of about 0.05 mm., which lies between the 1/16 and 1/32 mm. limits in the grade-scale. According to Von Hahn,⁴ Stokes' law is valid to within the limits of the colloidal state, despite Brownian movement, although a lower limit probably must be present, or colloidal suspensions would not be practically permanent, as they are. The limits of the colloidal state have been generally accepted to lie between 0.1 μ and 0.2 μ diameter, so that the smallest diameter shown in the table, which is 0.1 μ , is perhaps as small as one may safely go.

It is doubtful whether many sediments will be analyzed to this small size, because of the time involved.

These limits to the satisfactory operation of the pipette method require a special treatment of sediments having material larger than 1/16 mm. diameter. In such cases, as will be described in detail below, the coarser material is sieved from the sample before the standard suspension for pipetting is prepared. Sieves with meshes as small as 0.061 mm. are available at no great cost, and the writer has adopted the practice of using such a sieve to separate the samples into two parts, one for sieving, and the other for pipetting.

Another point that has a practical bearing on the accuracy of the pipette method concerns the nature of the sample obtained by the pipette. From purely theoretical grounds it is clear that the level sampled should be a horizontal stratum of depth h and essentially infinitesimal thinness. Practically, of course, a pipette taps a spherical zone, and various workers have endeavored to determine the amount of error introduced by this fact. The most outstanding contribution was made by Köhn,⁵ who photographed the process of pipette sampling, and was able to determine with some degree of accuracy the zone affected. He concluded that since part of the sphere is above the theoretical stratum, and part below, the error was essentially compensatory. Gessner⁶ discussed his findings, and pointed out that the error was of

³ Gessner, H., *Die Schlämmanalyse*, p. 21.

⁴ Hahn, F.-V. von, *Dispersoidanalyse*, p. 272.

⁵ Köhn, M., *Beiträge zur Theorie und Praxis der mechanischen Bodenanalyse*, *Landwirts. Jahrb.*, vol. 67, pp. 485-546, 1928.

⁶ Gessner, H., *op. cit.*, pp. 79 ff.

such a low order of magnitude that for a depth of 10 cm., and a sample of 10 cc., the error introduced was only 0.04 per cent. Keen⁷ has concurred in showing that the errors are practically negligible. The fact that the pipette method has been adopted as standard for soil analyses in England, America, and by an international commission, argues strongly in its favor.

Special devices for withdrawing the samples have been developed, but an ordinary pipette with a rubber tube for suction affords fully reliable results.

THE TECHNIQUE OF ANALYSIS

Since the pipette method involves a continuous sedimentation of the particles acting as individuals, it is clear that complete dispersion of the sample is an integral part of the method. A great number of techniques for securing dispersion have been advanced, but it is generally agreed that a thorough disaggregation of the particles, followed by their peptization through chemical agents, is the most satisfactory. The two steps have often been combined into one, but it appears to be advisable to take into account the nature of the material being analyzed in adopting a particular technique. The writer's experience has been confined mostly to glacial tills and other unconsolidated sediments like lake clays, and for such sediments the process to be described has proved to be consistently satisfactory.

Experiments with several methods of disaggregation have convinced the writer that a period of shaking in a

machine like that described by Briggs, Martin, and Pearce⁸ gives consistently good results. In lieu of this, pestling with a rubber-covered pestle or with a stiff brush may be substituted. In the procedure adopted, shaking a quartered sample for one hour with 100 cc. of a one per cent solution of sodium carbonate has been found sufficient to break up the aggregates and to leave the coarser grains free of any adhering clay. The weight of the sample used depends upon the amount of material greater than 1/16 mm. present in it. It is desirable to have a final concentration between 2 and 3 per cent for pipetting, so that the proportion of fine material in the quartered sample should lie between 20 and 30 grams for a liter of suspension.

After the sample has been shaken for an hour, it is poured through a sieve with meshes of 1/16 mm. (0.061 mm.), and the residue on the sieve is washed with a gentle stream of water. A liter beaker is used to collect the washings, and care should be exercised to keep the volume below 1000 cc. when the process is completed. The material on the sieve is washed into filter paper, dried, and weighed. The difference in weight between the original sample and the sieve residue is the amount of material finer than 1/16 mm.

In many cases shaking, combined with the peptizing effect of sodium carbonate, is sufficient to produce a completely dispersed suspension, but the results obtained are not always consistent even among samples of similar

⁷ Keen, B. A., *The physical properties of the soil*, p. 73.

⁸ Briggs, L. J., Martin, F. O., and Pearce, J. R., The centrifugal method of mechanical soil analysis, *U. S. Dept. Agric., Bureau of Soils, Bulletin 24*, 1904.

sediments. With tills it was found that complete dispersion could in many cases be induced only by heating the final suspension to the boiling point, but not allowing it to boil. The boiling of samples has many advocates and a number of critics; Von Hahn,⁹ indeed, refers to the "barbaric" practice of boiling suspensions, but others, such as Gessner,¹⁰ recognize its merits in some cases. There is little question that prolonged boiling coagulates some of the colloids, but it may be equally true that an increase in temperature, within certain limits, enhances the peptizing effect of the dispersing agent. To test this, the writer has heated samples to 60°C., and 80°C., but without effects as permanent as at 100°C. Some of the suspensions prepared by the adopted method still retain their colloids in suspension after a period of one year. After the preliminary treatment has been completed, the suspension is poured into a liter graduate and diluted to 1000 cc.

Various methods have been used to test for flocculation in a suspension, and among these one of the simplest is to place a drop on a slide and examine it under the microscope. If each grain stands out as an individual, and the smaller ones display Brownian movement, it is reasonably safe to consider the dispersion complete, while if aggregates or bead-like strings of particles extend through the field, the suspension is flocculated. The test is not always positive in the absence of flocules, because with small amounts of flocculants the suspensions may remain

apparently dispersed for several hours. The writer has adopted the practice of preparing the following day's suspensions in the afternoon, and allowing them to stand overnight. If visible flocculation has not occurred within 16 hours, the suspension may safely be considered completely dispersed. When flocculation occurs during the test period, a "fluffy" sediment is observed at the base of the suspension, lighter in color than that of the layer of coarse silt that also accumulates.

It will be noted that no provision has been made in this plan for the removal of carbonates in the samples during the preliminary treatment. It is to be emphasized that when primary carbonate particles are present, they should not be removed before the mechanical analysis is completed, because they are an integral part of the frequency distribution, and it would materially affect the data secured if they were first dissolved. That this effect is produced may readily be seen by considering the presence of arenaceous or argillaceous limestone fragments in the samples. Pretreatment with acid would disintegrate the grains and leave behind a residue of sand or clay which would load the smaller sizes at the expense of the larger, and thus result in an inaccurate picture of the sediment. When secondary carbonates occur, as in the cements of sandstones, they must of course be removed if the composition of the original sediment is desired. In cases where both primary and secondary carbonates are present, one can seldom be removed without also removing the other, and it is usually necessary to decide to remove either all

⁹ Hahn, F.-V. von, *op. cit.*, p. 23.

¹⁰ Gessner, H., *op. cit.*, p. 163.

or none before the analysis, depending upon the predominance of one or the other.

When it is certain that the sample is dispersed, the graduate containing the liter of suspension is well shaken and set at rest. The time is noted, and 1 minute 55 seconds later, 20 cc. are drawn into a pipette inserted exactly 10 cm. below the surface. The contents of the pipette are poured into a tared 50 cc. beaker, and evaporated to dryness on a hotplate having a temperature of about 100°C., so that the liquid does

not boil or spatter. The weight of the residue is determined, a correction added for the amount of sodium carbonate present, and the result multiplied by 50, to obtain the total weight of material finer than 1/32 mm., in the sample. The suspension is in the meantime again shaken, and allowed to stand for 7 minutes 40 seconds. Another 20 cc. are drawn off as before, and the weight of material under 1/64 mm. determined. By subtracting the second from the first, the weight of the 1/32-1/64 mm. grade is found. The process is repeated at the intervals and the depths shown in the table until essentially all of the sample has been divided into grades.

Weight of material finer than 1/16 mm.	
Weight of material finer than 1/32 mm.	
Difference: amount in 1/16-1/32 mm. grade	
Weight of material finer than 1/32 mm.	
Weight of material finer than 1/64 mm.	
Difference: amount in 1/32-1/64 mm. grade	

26.44 gm.
25.60 (from first beaker)
0.84 gm.
25.60 gm.
20.30 (from second beaker)
5.30 gm.

These weights may be converted into percentages for frequency diagrams or cumulative curves, and if the sample contains material larger than 1/16 mm. it is sieved into grades in accordance with the method proposed by Wentworth.¹¹ The two parts of the analysis are then combined into a single table or curve for the entire sample.

COMPARISON WITH OLDER METHODS

In order to compare the results obtained by the pipette method with those obtained from one of the older routines, three samples of a clayey till were dispersed by the method described above, and allowed to stand for 16 hours to test for possible flocculation.

¹¹ Wentworth, C. K., Methods of mechanical analysis of sediments, *Univ. Iowa, Studies in Nat. Hist.*, vol. 11, no. 11, 1926.

The following example of the first several separations will indicate the routine: one liter of suspension con-

COMPARISON OF PIPETTE AND SEDIMENTATION TUBE METHODS

Grades	Pipette: 1		Pipette: 2		Sedimentation Tube	
	Per cent	Cumulative Per cent	Per cent	Cumulative Per cent	Per cent	Cumulative Per cent
Above 1 mm.	3.4	3.4	3.3	3.3	4.0	4.0
1 -1/2	1.9	5.3	1.8	5.1	1.6	5.6
1/2 -1/4	2.3	7.6	2.3	7.4	2.3	7.9
1/4 -1/8	2.7	10.3	2.7	10.1	2.7	10.6
1/8 -1/16	2.5	12.8	2.5	12.6	2.4	13.0
1/16 -1/32	4.1	16.9	4.6	17.2	8.4	21.4
1/32 -1/64	6.5	23.4	7.2	24.4	18.6	40.0
1/64 -1/128	14.0	37.4	12.5	36.9	60.0*	100.0*
1/128-1/256	12.6	50.0	12.9	49.8		
1/256-1/1000	22.1	72.1	24.1	73.9		
Under 1/1000	27.9	100.0	26.1	100.0		

* The material below 1/64 mm. was grouped into a single size because of the difficulty of separating smaller grades.

Two of the samples were analyzed by the pipette method, and the third by a sedimentation method. In the latter method, the suspension was poured into a cylinder, and allowed to stand until all particles larger than 1/32 mm. could reach the bottom according to velocities computed by Stokes' law. The supernatant liquid was then siphoned off, and drained into another cylinder, to separate all particles larger than 1/64 mm. Fresh water, containing a concentration of sodium carbonate equal to that of the original suspension, was added six times to each cylinder, and the supernatant liquid was quite clear at the end of the sixth washing. The residue in the first cylinder was collected and dried, and sieved into grades as shown in the accompanying table.

The pipette analyses were run in the manner described in this paper, and in order to have some check on the analyses, concentrations of about 2.5 and 5 per cent were used, to allow for any effects of concentration on the final

results. The data obtained are also shown in the table.

It will be noted that the amounts of material in the sieved grades agree very closely in all three analyses, while in the smaller sizes there is a marked divergence between the sedimentation and pipette methods. This divergence is even more marked when the data are plotted as cumulative curves, as shown in figure 1. The curve of the sedimentation method departs widely

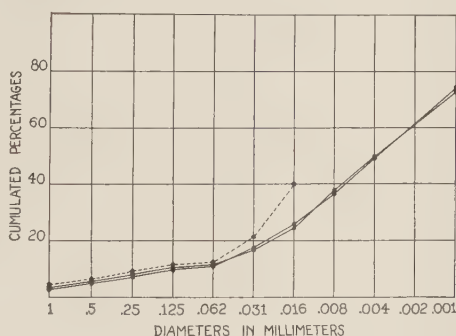


FIG. 1. Comparison of pipette and sedimentation tube methods on unaltered Wisconsin till. The solid lines represent the pipette analyses, and the broken line the sedimentation tube analysis.

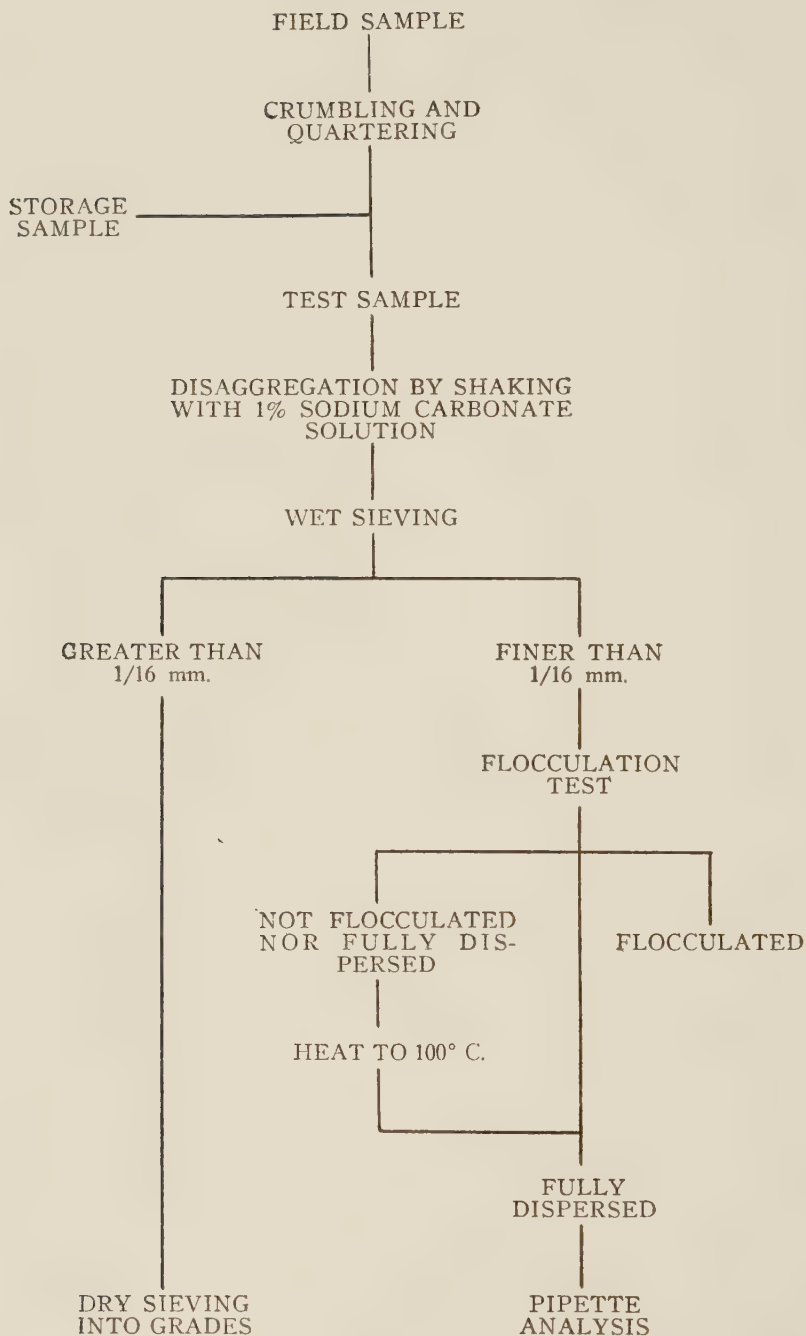


FIG. 2. Chart showing generalized routine of analysis.

from the pipette curves as soon as the sub-sieve sizes are reached. Attention is also called to the close parallelism of the two pipette analyses.

From these data it seems clear that the divergence of the upper curve from the other two is due to the fine material not separated from the two sedimented grades by the sedimentation method. If this is so, there is an error of more than 15 per cent in the analysis by the time the $1/64$ mm. limit is reached. An error of this magnitude is sufficient to call into question the advisability of using such decantation

methods for even approximate analyses.

SUMMARY

In order to summarize the steps involved in a pipette analysis, a flow sheet is shown in figure 2, which indicates them graphically. The steps involved include only those directly concerned with mechanical analysis, and do not include the determination of carbonates or the separation of heavy minerals, which may, however, be added to it if a more complete petrographic analysis is desired.

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TEXTURAL AND LITHOLOGICAL VARIATIONS IN GLACIAL TILL¹

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ABSTRACT

Till samples were collected from the Valparaiso moraine around the southern end of Lake Michigan, and along a line paralleling glacial movement from Chicago south. The samples were analyzed, and the pebbles classified according to lithology. In the Valparaiso moraine the mechanical composition was influenced by a loading of the ice with surficial material, and by drainage at the ice margin. The pebbles changed abruptly from dominantly limestone to shale and siltstone about 40 miles west of the corresponding bed rock contact. The westward movement of these pebbles was attributed to radial ice currents from the lake basin, over an area mantled with earlier drift. The samples in the line of glacial movement grouped themselves into three types on the basis of their mechanical composition. The results of the study are summarized in terms of the differentiation of tills by their textural composition. As an example of the method, the thickness of the Bloomington above earlier Wisconsin drift was determined in the absence of any intermediate weathered zone.

INTRODUCTION

The present paper has for its purpose an investigation of the textural and lithological variations in related samples of glacial till to determine the extent of variation in the line of glacial movement and at right angles to it. These variations are summarized in terms of the possible differentiation or correlation of such deposits. Two related areas were chosen in the eastern part of Illinois and in parts of Indiana and Michigan. A narrow strip in east-central Illinois was selected for the samples in the line of glacial movement, because it is crossed by ten moraines whose relative ages are clearly known. Further, bed rock differences occur along the traverse, and can be related to the textural and lithological variations in the till. The Valparaiso moraine was chosen for the study of lateral variation, both because it constitutes one of the moraines in the first traverse, and because it extends as a practically uninterrupted belt around the southern end of Lake Michigan. The bed rock underlying the Valparaiso moraine also undergoes a prominent change in western Indiana, and the effect of this change on the composition of the till may be considered.

¹ Published with the permission of the Chief, Illinois State Geological Survey.

The sampling areas are shown in their relation to the surrounding territory in Figure 1. Those parts of the moraines directly concerned with the study are shown in solid lines; adjacent field relations are merely indicated for purposes of orientation. It is clear that the Valparaiso moraine trends at right angles to the direction of movement of the ice sheet that deposited it. Similarly, the north-south line of sampling lies in the approximate line of glacial movement, as determined by Leverett and Taylor.²

In collecting the samples, road cuts or drill holes were used, and the samples were taken as far as possible, from zone 5 of the soil profile³ or where this was not feasible, from zone 4 below the region of secondary lime concretions. Thus all of the samples are unleached, and most are unoxidized. In all cases the samples were taken from as near the surface as the development of the soil profile would permit, in order to avoid the possibility of unknowingly obtaining samples of older till. The field samples averaged from one to two kilograms each, and were preserved in No. 5 brown Kraft paper bags. To obtain the samples, the slump of the road cut was cleared off over an area of 1 or 2 square feet, and a composite sample was secured by detaching pickfuls over this area. Care was exercised to obtain all of a given fragment, to make certain that no pebbles or lumps of clay were lost. Sampling was done on the crests or distal slopes of the moraines, in order to have topographically comparable samples. Till-plain samples were usually taken from stream cuts or drainage ditches.

More than one sample was taken from most moraines in the traverse along the line of glacial movement, and a few samples were collected from intervening till plains. In deciding on the interval between samples along the Valparaiso moraine, preliminary studies were made on samples taken from a till ridge constituting one of its members. It was found over a length of 40 miles that samples taken at intervals of 1 or 2 miles showed only slight changes in composition from one sample to the next. The study indicated that intervals

² F. Leverett and F. B. Taylor, "The Pleistocene of Indiana and Michigan," *U.S. Geol. Surv. Mono.* 53 (1915), Plate V, p. 62.

³ M. M. Leighton and P. MacClintock, "Weathered Zones of the Drift-sheets of Illinois," *Jour. Geol.*, Vol. XXXVIII (1930), pp. 28-53.



FIG. 1.—Map showing locations of samples

of 10 miles would not be too great if a considerable length of moraine was involved. In the present case the samples from the Valparaiso moraine average about 7 miles apart along a distance of 165 miles. In the laboratory the samples were crumbled into walnut-sized pieces and air dried. The dried pieces were then crushed with a rubber-tipped pestle until the fragments, excepting the larger pebbles, would pass through an 8 mm. sieve. The field sample was quartered with a Jones sample splitter until a laboratory sample of from 35 to 45 grams was obtained. The laboratory sample was analyzed by the pipette method in accordance with a technique recently described by the writer.⁴

VARIATION ALONG THE VALPARAISO MORAINE

Twenty-four samples of till from localities near the margin of the Valparaiso moraine were collected and analyzed. Figure 1 shows the sampling sites, and it will be noted that the samples extend around the lake from Elgin, Illinois, on the northwest, to Benton Harbor, Michigan, on the northeast. The samples were separated by intervals of from 4 to 10 miles, with an average interval of 7 miles. The average depth from which the samples were taken was 4 feet, and with few exceptions they were within zone 5 of the soil profile. They were collected from the distal half of the moraine, and most of them were secured within a mile of the distal edge.

The choice of the precise localities where samples were taken deserves some discussion. The till comprising the moraine was observed to undergo several striking changes as the moraine was followed along its extent. In its northwestern part, near Elgin, the moraine is composed almost entirely of a limestone gravel, and no exposures of clayey till were noted. Nevertheless, the moraine preserves its knob and kettle topography, and the material appears to be largely unbedded. South of the Fox River the till becomes more clayey in its appearance, and this condition persists without noticeable change until the Indiana state line is crossed. Near Valparaiso the moraine becomes quite sandy over large areas, with here and there a small area of typically clayey till. The sandy material is ap-

⁴ W. C. Krumbein, "The Mechanical Analysis of Fine-Grained Sediments," *Jour. Sed. Petrology*, Vol. II (1932), pp. 140-49.

parently unbedded, and preserves the form of morainic swells and knobs, but it does not resemble typical till. East of Valparaiso the sandy nature of the material increases, and the morainic edge becomes more elusive, with wide flats extending for considerable distances into the moraine, giving the outer edge a peculiar finger-like pattern. Drainage ditches disclose that the flats are composed of gravel, and the morainic "fingers" that separate them are often quite sandy but structureless. Even here, however, small areas of clayey till were found. Farther east, beyond La Porte, the morainic edge becomes more distinct again, and the till assumes a more clayey character, although lenses of sand and gravel are not uncommon. In Michigan, southeast of Benton Harbor, the sandy and gravelly phases again predominate, but there also are found scattered areas of clayey till.

It appears from these considerations that the drainage conditions varied considerably along the extent of the moraine, and it may be expected that the mechanical composition of the tills was influenced by these factors. Under conditions of vigorous drainage the fine material is presumably washed from the till, and because of the variations noted, it was deemed advisable to confine the sampling, as far as possible, to areas of clayey till. By this means the effects of unusual drainage conditions would not color the conclusions advanced concerning a deposit assumed to have been laid directly by the ice.

Factors other than varying drainage conditions have influenced the composition of the till, and among these may be mentioned the underlying bed rock and the surficial material picked up by the advancing ice. Studies of the exposures between Valparaiso and La Porte disclosed that in some places the sand content of the till is so high that it appears to indicate the assimilation of dunes by the advancing ice. Further, sand dunes are quite common along the proximate edge of the moraine in this vicinity, but the distance to the present shore of Lake Michigan is too great to assume the migration of dunes from there. It appears more likely that after the melting back of the ice, the high sand content of the till favored wind action before vegetation gained a foothold. Leverett⁵ noted the sandy

⁵ F. Leverett, "The Illinois Glacial Lobe," *U.S. Geol. Surv. Mono.* 38 (1899), pp. 356-57.

nature of the till in this locality, and he mentioned Taylor's suggestion that it was due to a loading of the ice with sand from dunes along the then shore of a pre-Valparaiso lake: a conclusion with which the present writer concurs. The bearing of the analytical data on this hypothesis will be touched upon later.

STATISTICAL TREATMENT OF THE DATA

The results of the mechanical analyses of the samples are shown in Table I. For convenience the north-south samples are included in the same table, but they will be discussed later. The data are arranged as percentages by weight in the several grades, and for ease of tabulation and plotting, the material larger than 1 mm. is combined in a single column. The data may be more readily visualized in graphic form, and Figure 2 shows the cumulative curves of the Valparaiso samples. It will be noted that the curves as a whole move across the chart fairly smoothly, and constitute a broad band, in which most of the members are approximately parallel, but several exceptions occur.

Six of the curves vary noticeably, in part at least, from the trends of the remaining curves. These are samples number 4, 15, 16, 22, 23, and 24, so numbered in Figure 2. Number 4 follows the main trend in the smaller ranges, and lags behind the others in the sand and gravel sizes, due to a larger proportion of coarse material. The general appearance of the till exposure from which the sample was taken was not different from that of the adjacent ones, but several large pebbles were noted in the sample analyzed. Inasmuch as the curve in the smaller ranges does not depart noticeably from the others, the variation is not due to the washing out of finer material, but probably represents a local loading of coarse material in the till. Numbers 15 and 16 were taken from the sandy part of the moraine in western Indiana, and the irregularities in these two samples are due to high percentages of sand. The smoothness of the curves in the finer ranges also is not materially upset, so that these as well show no washing out of the finer material, but a loading of the particular sand sizes instead. The sand ranges which are represented occur in dune sand, and this feature apparently corroborates the notion that surficial sand deposits contributed to the composition of the till here. Sample 22 is the lowermost curve in the smaller ranges, but rapidly

TABLE I
MECHANICAL ANALYSES OF ALL SAMPLES

SAMPLE	GRADE SIZES IN MILLIMETERS										
	Above 1 mm.	1 to 1/2	1/2 to 1/4	1/4 to 1/8	1/8 to 1/16	1/16 to 1/32	1/32 to 1/64	1/64 to 1/128	1/128 to 1/250	1/250 to 1/1000	Below 1/1000
1.....	10.0	2.6	3.9	4.8	4.7	9.9	11.9	13.3	10.2	12.9	15.8
2.....	9.3	2.0	2.9	3.5	3.1	8.9	10.5	12.3	11.0	17.9	18.6
3.....	8.6	2.8	3.7	3.7	3.0	6.5	9.0	10.7	11.3	19.6	21.4
4.....	19.0	1.7	2.7	3.6	4.2	8.8	8.7	9.9	9.0	13.7	18.7
5.....	4.2	1.4	1.8	2.3	2.4	4.7	10.8	16.5	14.9	20.7	20.3
6.....	4.6	1.9	2.3	2.7	3.1	6.3	13.0	15.7	12.0	19.9	18.5
7.....	4.8	1.1	3.8	3.3	1.9	7.9	10.5	13.7	12.9	18.9	21.2
8.....	5.3	3.2	4.1	4.3	3.3	10.5	14.0	18.2	11.7	11.4	14.0
9.....	4.2	2.0	2.5	2.9	3.3	10.2	11.9	13.5	12.4	16.0	21.1
10.....	5.4	1.2	1.5	2.4	2.9	8.4	9.6	14.9	11.0	18.7	24.0
11.....	3.0	1.4	2.0	3.4	3.3	5.4	9.2	13.0	11.5	23.4	24.4
12.....	3.2	2.1	3.7	4.0	2.3	8.1	13.9	11.5	11.0	17.1	23.1
13.....	5.0	1.8	2.8	3.8	3.5	8.8	13.8	16.8	12.6	13.6	17.5
14.....	4.1	1.7	3.2	5.2	5.6	12.2	11.5	12.4	10.5	15.0	18.6
15.....	4.1	1.9	10.0	11.2	5.7	13.9	11.7	10.1	5.9	10.4	15.0
16.....	4.1	2.2	7.6	9.5	7.2	13.3	9.8	10.5	8.9	9.4	17.5
17.....	2.6	1.3	3.8	4.9	3.7	8.1	12.5	12.7	10.7	16.1	23.6
18.....	1.6	1.6	5.7	6.6	3.4	6.9	7.8	11.5	11.7	19.4	23.8
19.....	1.9	1.1	2.0	3.6	3.6	8.0	10.3	13.7	13.2	20.4	22.2
20.....	2.6	1.7	3.8	4.9	3.9	8.3	14.0	14.9	13.0	14.4	18.5
21.....	6.6	1.7	3.5	6.0	6.2	11.7	9.6	11.7	10.6	14.6	17.8
22.....	4.8	2.1	4.9	8.4	7.8	19.4	16.0	11.5	7.3	8.7	9.1
23.....	2.3	1.9	9.0	12.2	5.4	9.5	8.2	9.3	7.5	17.7	17.0
24.....	2.7	2.5	10.5	15.9	7.2	6.1	5.9	4.3	8.1	16.7	20.1
A.....	13.9	6.9	15.5	15.1	9.3	7.9	11.0	6.7	3.6	4.3	5.7
B.....	10.2	6.2	14.7	14.9	9.9	10.0	8.8	7.3	4.6	6.4	7.0
C.....	8.6	4.7	11.8	14.5	9.2	8.5	12.2	7.2	5.5	7.8	10.0
D.....	6.3	4.1	12.8	14.6	12.0	9.6	13.8	7.7	5.2	5.7	8.0
E.....	10.2	5.0	11.1	11.8	8.3	8.3	11.0	8.2	6.4	8.9	10.8
F.....	9.8	4.4	9.1	9.3	6.3	6.9	11.2	11.5	9.4	10.0	12.2
G.....	19.7	4.5	9.9	9.6	7.1	10.3	9.8	8.9	5.9	6.7	7.3
H.....	13.0	4.1	10.0	10.8	8.3	7.8	10.9	10.4	9.5	5.9	9.3
I.....	9.5	5.5	13.2	12.4	7.0	6.0	11.3	8.1	7.5	7.1	12.2
J.....	4.7	2.8	5.0	4.8	3.4	7.6	11.2	15.2	12.2	16.3	16.8
K.....	5.8	3.2	4.5	4.9	3.8	8.8	10.2	17.6	14.4	13.0	13.0
L.....	7.9	3.1	5.6	5.0	3.7	7.3	9.5	16.9	11.1	16.1	13.8
M.....	5.8	2.0	2.9	3.2	3.4	5.8	10.1	21.1	12.1	18.5	15.3
N.....	7.9	4.3	5.9	5.3	3.7	9.6	8.2	17.2	14.6	10.5	12.8
O.....	3.7	2.1	3.0	3.2	2.8	5.1	7.6	20.2	16.9	17.4	18.0
P.....	2.1	1.2	1.7	2.0	1.8	2.9	7.7	14.7	16.5	22.9	26.6
P ₁	4.0	1.0	1.1	1.6	1.3	3.9	6.0	11.2	12.3	23.4	24.1
Q.....	4.9	1.9	2.6	2.7	2.3	5.9	8.7	13.8	14.5	18.9	23.8
R.....	1.1	0.6	0.8	1.1	1.0	5.0	6.5	12.3	16.1	25.5	30.0
S.....	2.1	0.7	1.1	1.8	2.0	8.4	7.8	11.3	12.5	21.2	31.1
T.....	2.6	0.7	1.0	1.2	2.3	11.2	11.0	14.0	12.9	19.2	23.8
U.....	0.5	1.1	2.4	4.8	3.2	3.6	8.1	14.7	12.9	24.6	24.1
V.....	3.0	1.4	2.0	3.4	3.3	5.4	9.2	13.0	11.5	23.4	24.4
W.....	0.7	0.9	1.1	2.9	3.0	3.7	9.6	12.8	13.4	25.5	26.4

risers through the silt and finer sand sizes, to become one of the uppermost curves at the coarse end of the range. The low percentage of clay in this sample suggests that the finer material may in part have washed out due to drainage conditions at the time of deposition. Sample 23 is similar to 15 and 16, and from the field relations it appears that sand assimilation also occurred along the moraine southeast of Benton Harbor. Sample 24 departs most widely from the general trend of the curves. It has the average amount of clay,

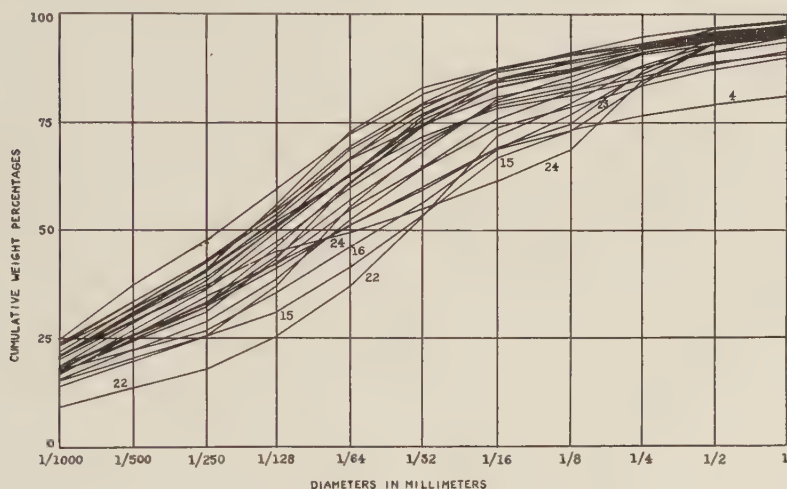


FIG. 2.—Cumulative curves of Valparaiso samples

but a striking decrease in the silt, and an increased amount of sand. The cause of this single variation is not known, and it would be hazardous to postulate a washing out of the silt without effecting a corresponding reduction of the clay. A noteworthy feature of the cumulative curves is that they show no systematic variation from one sample to the next, but appear to deviate within certain limits from a mean composition.

A qualitative comparison of cumulative curves may serve to bring out general relations, but it is desirable to have some means of comparing the samples more quantitatively. Such a device is available in the statistical treatment of the data, which furnishes a series of values for each sample. The nature of the frequency data imposes limitations on the significance of the statistical values obtained, and it is

important to recognize this point. It may be pointed out that the statistical values decrease in significance with an increase in the irregularity of the frequency curve. Tills have extremely irregular distributions, and the presence of several secondary maxima render them polymodal in aspect. Such polymodal curves may be due to several factors, but in tills they are probably due to a mixture of several distributions behaving under different laws, and contributed by the material picked up by the ice in its forward movement. Because of the composite nature of the data, a generalized method of statistical treatment has been used, so that the characteristics determined have at least the significance necessary to permit a comparison among the samples. The method used involves the median and the quartiles, which are read directly from the cumulative curve. The median represents the middle grain size, and the quartiles represent the grains one-fourth and three-fourths of the way along the range. The median may thus be used as an average grain size, and the quartile deviation as a measure of the scattering of the data. Trask⁶ has discussed the application of median and quartiles to the analysis of sedimentary data, and has developed formulas for sorting and skewness. The writer has used the common equation $QD = \frac{Q_3 - Q_1}{2}$ for determining the quartile deviation of the samples in the present paper.

The medians, quartiles, and quartile deviations of all the samples studied are shown in Table II. It will be noted that the medians of the Valparaiso samples range in value from 0.0044 to 0.027. This represents the diameter in millimeters of the average grain size, and the range falls entirely within the silt sizes, whose limits are generally accepted as lying between 0.004 and 0.06 mm. diameter. Such a table of statistical values is not an end in itself when an entire suite of samples is considered. Various devices may be used to point out the significance of the data in physical terms, and among them the median procession curve is useful for indicating the variation in the average grain size as the samples are followed along the moraine. The medians are plotted as ordinates and the miles between succes-

⁶ P. D. Trask, "Studies of Recent Marine Sediments conducted by the American Petroleum Institute," *Bull. 89, Nat. Research Council* (1932), pp. 60-67.

TABLE II
STATISTICAL CONSTANTS OF THE SAMPLES

Sample	Median	First Quartile	Third Quartile	Quartile Deviation
1.....	0.0135	0.0027	0.073	0.0351
2.....	.0090	.0017	.045	.0216
3.....	.0069	.0013	.045	.0218
4.....	.0142	.0019	.185	.0916
5.....	.0058	.0014	.018	.0083
6.....	.0075	.0016	.025	.0117
7.....	.0066	.0014	.027	.0128
8.....	.0130	.0037	.046	.0212
9.....	.0079	.0014	.012	.0153
10.....	.0061	.0011	.024	.0114
11.....	.0044	.0011	.019	.0089
12.....	.0072	.0012	.029	.0139
13.....	.0100	.0021	.033	.0154
14.....	.0110	.0019	.046	.0221
15.....	.0260	.0039	.140	.0680
16.....	.0200	.0031	.110	.0534
17.....	.0074	.0012	.030	.0144
18.....	.0060	.0011	.034	.0164
19.....	.0058	.0012	.023	.0109
20.....	.0093	.0019	.032	.0150
21.....	.0120	.0021	.060	.0289
22.....	.0270	.0075	.084	.0382
23.....	.0140	.0018	.130	.0641
24.....	.0170	.0015	.170	.0842
A.....	.1330	.0205	.420	.1998
B.....	.0940	.0150	.340	.1630
C.....	.0560	.0092	.252	.1214
D.....	.0620	.0131	.232	.1095
E.....	.0470	.0069	.280	.1366
F.....	.0235	.0048	.225	.1101
G.....	.0660	.0120	.480	.2340
H.....	.0440	.0079	.295	.1436
I.....	.0460	.0064	.295	.1433
J.....	.0100	.0021	.045	.0220
K.....	.0110	.0033	.052	.0244
L.....	.0112	.0026	.066	.0322
M.....	.0090	.0021	.013	.0127
N.....	.0125	.0042	.094	.0454
O.....	.0070	.0017	.020	.0092
P.....	.0041	.0009*	.012	.0055
P _r	.0027	.0006*	.011	.0052
Q.....	.0056	.0011	.022	.0105
R.....	.0030	.0008*	.009	.0043
S.....	.0034	.0006*	.015	.0070
T.....	.0056	.0010	.022	.0105
U.....	.0047	.0010	.014	.0065
V.....	.0044	.0011	.019	.0089
W.....	.0036	.0009*	.013	.0060

* By extrapolation.

sive samples as abscissae, as shown in Figure 3. The curve shows a certain rhythmic tendency, inasmuch as the medians of the samples vary between troughs and peaks in their course along the moraine. Several of the peaks may be identified as being due to special circumstances. Samples 4, 15, 16, 22, 23, and 24 are all higher than the average values. These samples were mentioned earlier as having erratic cumulative curves, and the high values of the medians are related to the shifting of the curves due to the loading factors mentioned. In addition, samples 1, 8, 14, and 21 are higher than the



FIG. 3.—Median curve of Valparaiso samples

average value. Whether these latter high values represent some rhythmic fluctuations in the composition of the till, or whether they are fortuitous variations due to sampling errors, is a point on which it may not be safe to offer an opinion. The suggestion is strong, however, that drainage from the ice, concentrated at several points along the moraine, may have increased the general coarseness of the till by washing out varying amounts of the finer material. It is curious in this connection that the intervals between such successive high points should be of approximately equal length.

THE LITHOLOGIC COMPOSITION OF THE TILL

The areal geology maps of Illinois, Indiana, and Michigan show that the bed rock underlying the Valparaiso moraine undergoes a pronounced change a short distance west of Valparaiso. The western half of the moraine, in Illinois and in the western part of Indiana, is underlain by Silurian limestone and dolomite. Between Valparaiso

and a point southeast of Benton Harbor the bed rock is predominantly a black Devonian shale, and north of that point to beyond the edge of Figure 1, the bed rock is gray to blue Mississippian shale. West of the main contact between the Silurian and Devonian in western Indiana occur local areas of Devonian siltstone and shale, which appear to extend into the eastern part of Illinois.⁷ Similarly, the bed rock in Indiana, while predominantly shale, is locally a Devonian(?) limestone, as at Michigan City, where a well penetrated limestone beneath the glacial drift.⁸

On the assumption that tills reflect the bed rock in the lithologic composition of their pebbles, it may be anticipated that a striking change in the pebbles should take place somewhere in western Indiana, so that to the west, limestone should predominate, whereas to the east shales and siltstones should constitute the major part of the pebbles. The percentage of limestone may be expected to increase in the vicinity of Michigan City also. To determine whether this condition exists, a sample of all pebbles larger than 2 mm. was washed from each sample of till, and classified into lithologic types. The samples ranged from 200 to 500 pebbles each, and the results were expressed as percentages. Several types of pebbles were noted in the samples, which were divided into the following groups:

a) *Limestone pebbles*, which included mainly gray to buff dolomitic limestone, but dark gray pebbles, and some rather soft yellowish pebbles were present. These pebbles were tested with warm hydrochloric acid.

b) *Shale and siltstone pebbles*, which ranged from fine-grained black shale to typical siltstones. The siltstones are mainly drab to buff, and are often silty shales, sometimes feebly calcareous. Some gray shale pebbles were also noted. It was not expedient to separate the siltstones from the shales, owing to the gradations present.

c) *Crystalline pebbles*, which included igneous and metamorphic rocks, as well as fragments of quartz, feldspar, and the like. These pebbles constitute the erratic portions of the pebbles.

d) *Miscellaneous pebbles*, including the cherts, the altered pebbles, and a few which could not be classified elsewhere.

The results of the pebble counts are shown in the first half of Table III. In Figure 4 the data are plotted: the types of pebbles by per-

⁷ Unpublished data of the Illinois State Geological Survey.

⁸ W. N. Logan, *Petroleum and Natural Gas in Indiana*, Indiana Division of Geology (1920), p. 164.

TABLE III
PERCENTAGES OF PEBBLES BY COUNT

Sample	Limestone	Siltstone and Shale	Crystallines	Miscellaneous
1.....	79.2	13.6	3.6	3.6
2.....	82.9	10.2	4.0	2.9
3.....	84.7	9.7	2.6	3.1
4.....	83.7	9.4	2.3	4.6
5.....	87.5	6.8	3.1	2.6
6.....	82.1	11.2	3.9	2.8
7.....	42.0	49.0	5.0	4.0
8.....	7.6	89.4	3.0	0.0
9.....	9.9	80.7	4.5	4.9
10.....	11.4	83.4	3.1	2.1
11.....	14.1	81.1	3.2	1.6
12.....	11.6	79.9	6.8	1.7
13.....	8.8	83.5	3.7	3.1
14.....	10.3	83.0	3.5	2.7
15.....	7.3	84.9	3.2	4.6
16.....	2.9	86.9	3.7	6.5
17.....	3.8	80.5	9.2	6.5
18.....	3.2	73.9	13.5	9.4
19.....	10.0	79.8	6.7	3.5
20.....	23.2	65.9	6.9	4.2
21.....	23.4	62.9	7.5	6.2
22.....	21.6	64.5	8.7	5.2
23.....	0.0	72.8	13.3	13.9
24.....	11.0	45.7	20.0	23.3
A.....	13.3	57.0	18.0	11.7
B.....	12.2	61.3	13.9	12.6
C.....	15.6	55.8	16.0	12.6
D.....	9.6	65.5	12.7	12.2
E.....	18.0	52.0	18.9	11.2
F.....	14.2	58.6	19.8	7.4
G.....	14.6	63.6	11.8	10.0
H.....	19.8	54.1	14.9	11.2
I.....	16.6	62.5	15.9	5.0
J.....	10.3	79.4	6.4	3.9
K.....	10.9	78.1	6.5	3.5
L.....	13.4	67.1	6.6	2.9
M.....	7.8	85.9	4.8	1.5
N.....	7.9	86.1	4.4	1.6
O.....	10.5	84.3	4.1	1.1
P.....	7.3	86.6	4.5	1.6
P ₁	25.3	70.6	1.8	2.3
Q.....	15.2	79.6	2.5	2.7
R.....	41.8	61.5	5.1	0.0
S.....	36.7	57.6	1.3	4.4
T.....	9.0	87.4	2.0	1.6
U.....	22.9	65.2	6.8	5.1
V.....	14.1	81.1	3.2	1.6
W.....	17.1	76.8	3.7	2.4

centages as ordinates and miles between samples as abscissae. The miscellaneous group is not included in the graph. It is apparent at a glance that the limestone curve drops rather abruptly in its course along the moraine, and that the shale and siltstone curve rises equally as abruptly. The curve of the crystallines, on the other hand, shows no abrupt change in its trend.

When the curves are examined in detail, it is noted that the prominent drop in the limestone content, from 80 to 10 per cent, occurs

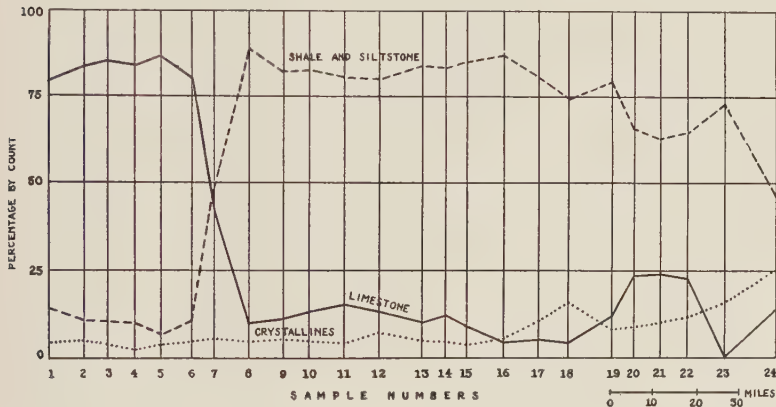


FIG. 4.—Lithology curves of Valparaiso samples

over a distance of about 13 miles, southeast of Joliet. In this same distance the shale and siltstone curve has its prominent rise. After following along at a low level for a number of miles, the limestone curve rises again, but drops almost to zero near the end of its course. The shale and siltstone curve, in the meanwhile, maintains its high level and only drops toward the end. The crystallines begin to increase in number near sample 16, and after some fluctuation, the curve swings up to 20 per cent of the pebble content.

The most striking feature in the diagram is that the point of intersection of the limestone and shale curves takes place not at the contact between the two types of bed rock, but about 40 miles west of it. This means that, although the bed rock is limestone under some 40 miles of the moraine, the predominant pebbles in the till are not limestone, but shale and siltstone. This condition appears to be due to

the relation between the sites of active erosion by the ice and the sites of deposition. That is, if the active erosion of bed rock was confined to the basin of Lake Michigan, and if the site of the moraine was covered by earlier drift, the westward currents of ice would carry shales and siltstones over the protected area to the west. Leverett⁹ lists the depths to bed rock at several points along the moraine, and he expresses the opinion that some of the drift is undoubtedly of pre-Valparaiso age. His figures show that the total depth of the drift is from 100 to 300 feet, and of this he assigns about 65 feet to the Valparaiso. Thus a protective covering appears to have been present.

The contact between the Silurian and Devonian enters the southern edge of the lake near the Illinois-Indiana line, and hence lies in the western part of the basin. The presence of remnants of Devonian bed rock at Milwaukee suggests strongly that the contact continues in the western part of the basin throughout its extent in the area involved. Such a relation would clearly influence the westward transportation of shale and siltstone. Since the movement of the ice is radial from the central part of a lobe, the active erosion of shales in the western part of the basin would load the ice with pebbles of that composition, and they would still predominate in the drift-covered area above the limestone. The effect of this ice movement would be most strongly felt in the southwestern part of the lobe, because in those parts where the ice moved approximately due west the exposed limestone in the lake basin would effectively control the pebble content of the ice.

The change between a predominance of limestone and a predominance of shale and siltstone occurs over a zone only 13 miles wide. It appears from this that the width of the zone is largely a function of the distance traveled by the ice after the heavy loading of local material. In the present case the distance from the contact in the southern part of the lake basin to the edge of the moraine is only a matter of 40 to 50 miles. It is believed that the transition zone would have been appreciably wider if the moraine were farther from the contact.

The rise in the limestone curve farther east is undoubtedly related

⁹ F. Leverett, *op. cit.*, pp. 353-55.

to the limestone bed rock which occurs beneath the drift at Michigan City. The rise in the crystalline curve near the northeastern end of the series is not readily explained. The relatively smooth increase in the curve argues against errors introduced by sampling. Since there are no known areas of crystalline rocks within several hundred miles of the area, there seems to be no simple explanation for the phenomenon.

In tying together the lithological and textural compositions of the till, it may be anticipated that a relatively resistant rock-like limestone would furnish large pebbles, while a softer shale would be ground down to silt and clay, and load the finer ranges. Curiously enough, no such situation was reflected in the samples. Attention is called again to the median procession curve (Fig. 3), in which the average sizes of the distributions were shown. It is interesting to note that in the same distance where the limestone decreases, the medians increase in value.

On the whole it seems that unconsolidated surficial materials in the path of the ice have a greater effect on the textural composition than indurated bed rock, even when the latter is a relatively soft shale. This seems to be borne out by the strong effect of the dune sand near Valparaiso, which appreciably shifted the median values of the curves, and distorted them beyond the usual limits of deviation. Next to the loading of surficial materials has been the effect of drainage along the ice margin. This effect has been secondary in the present study, because the samples were chosen to represent tills unaffected by varying drainage conditions, but it has not been possible to eliminate them entirely. Despite the attempted control of the drainage factor, it has appeared in the curves more strongly than the effects either of the underlying bed rock or of the lithological composition of the pebbles in the till. If perfectly random samples had been chosen, there is no doubt that the curves would have departed much more widely from the average composition.

VARIATION IN THE LINE OF GLACIAL MOVEMENT

Twenty-three samples of till arranged in the approximate line of glacial movement were collected and analyzed. Figure 1 shows the sampling sites, which extend from a point south of Chicago to be-

yond Paris. In order that the moraines traversed may be familiar to the reader, it should be pointed out that samples *A* and *B* were taken from the Shelbyville moraine, *C* and *D* from the Cerro Gordo moraine, *F*, *G*, and *H* from the Champaign moraine, *J*, *K*, and *L* from the outer Bloomington moraine, *M* and *N* from the Cropsey ridge (middle Bloomington of Leverett), *O* and *P* from the Chatsworth ridge (inner Bloomington of Leverett), *Q*, *R*, and *S* from the Mar-seilles moraine, *T* from the Rockdale moraine, *U* from the Manhat-tan moraine, *V* (which is identical with sample 11) from the outer

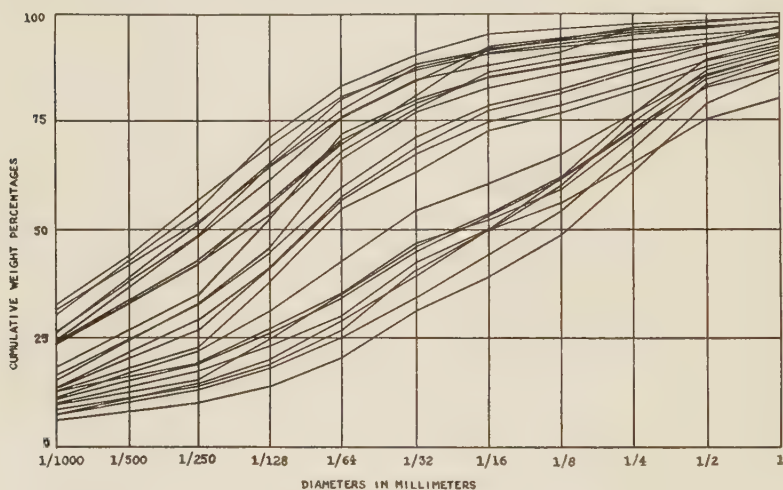


FIG. 5—Cumulative curves of north-south samples

Valparaiso moraine, and *W* from the inner Valparaiso or Tinley moraine.

In general, the samples were taken from parts of the moraine not directly associated with outwash channels in order to avoid complexities arising from drainage factors affecting the composition of the till.

STATISTICAL TREATMENT OF THE DATA

The results of the mechanical analyses of the samples are shown in Table I. Figure 5 illustrates the cumulative curves of the suite, and it may be seen that they divide themselves into three groups. The first group, represented by the nine lowermost curves, includes only

samples *A* to *I*. Of the upper fifteen curves, six depart from the general trend in the finer ranges, but merge with the others in the coarser grades. The six middlemost curves include only samples from *J* to *O*, and the uppermost curves are samples *P* to *W*. It may be seen from these curves that there is a strong suggestion of three types of till, and when the data are arranged in a triangle diagram, as in Figure 6, this cleavage into types stands out more clearly. The samples in the diagram are arranged according to their percentages of gravel and sand, silt, and clay, and it will be noted that samples *A* to *I* form the uppermost group, and that there is no overlap between this group and the other two. The samples below tend to arrange themselves into two groups, but there is some overlap present.

If the samples are considered in terms of moraines, it is seen that the uppermost group includes moraines of Shelbyville, Cerro Gordo, and Champaign ages. The central group has the outer Bloomington and the Cropsey ridges, and one sample from the Chatsworth ridge (*O*). Sample *P*, also from the Cropsey, falls in with the more northern moraines, which constitute the third group. Hence if three types of till are present, the boundary between the first and second is quite clear, but the data overlap with respect to the second and third. For convenience the three types of till will be referred to as the "Southern," "Middle," and "Northern," respectively.

When the statistical data of the samples, as shown in Table II, are considered, the break between the "Southern" and "Middle" types is clearly brought out. Figure 7 shows the median values of the samples as ordinates and miles between samples as abscissae. Inasmuch as more than one sample of some moraines are involved, the values

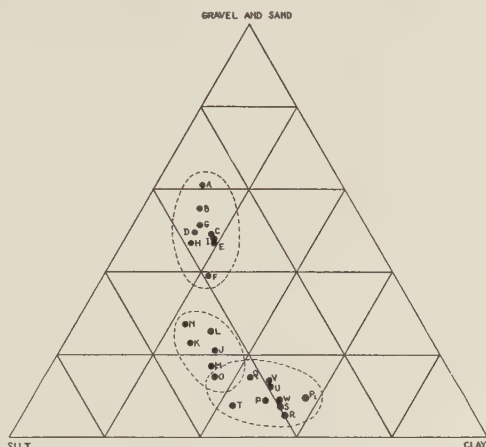


FIG. 6.—Triangle diagram of north-south samples

in such cases were averaged, and the number of samples in each average is indicated below the corresponding ordinate. The medians decrease rapidly along a curve from sample *A* to *I*, and over the very short interval between *I* and the next ordinate, there is a sharp drop to the Bloomington values. This marks the break between the "Southern" and "Middle" types. The extremely high values of *A* and *B* are difficult to explain, but it is possible that they show the effects of ice-margin drainage. Another minor drop occurs between

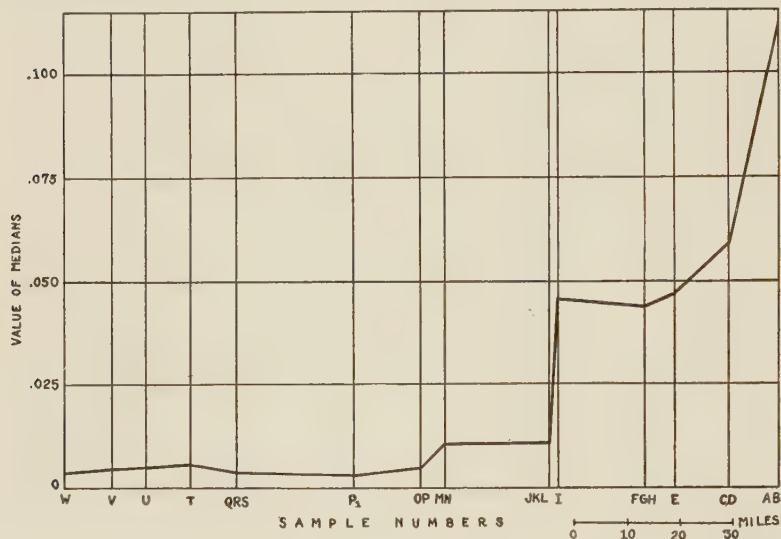


FIG. 7.—Median curve of north-south samples

the Cropsey and Chatsworth ridges, and from there north the values fluctuate but slightly. The position of the second break in the diagram indicates that the outer Bloomington and Cropsey ridges should constitute the "Middle" type, and that the Chatsworth and all moraines to the north should be classified as the "Northern" type.

THE LITHOLOGICAL COMPOSITION OF THE TILL

In order to supplement the data furnished by the mechanical analyses, pebbles were counted in a manner similar to that described in the case of the Valparaiso samples. The data are shown in Table III, and in Figure 8 the curves are plotted. In all three curves there

is a sharp break between the "Southern" and "Middle" samples. This substantiates the conclusion that the tills differ from each other. In attempting to relate the curves to the "Northern" type of till, it is found that the sharp break occurs not at the Chatsworth ridge, but in the till plain north of it. Since the contact between the Silurian limestone and dolomite and the Pennsylvanian bed rock occurs at a point south of Watseka, all samples from P_1 to W inclusive are underlain by the Silurian, and those farther south by Pennsylvanian

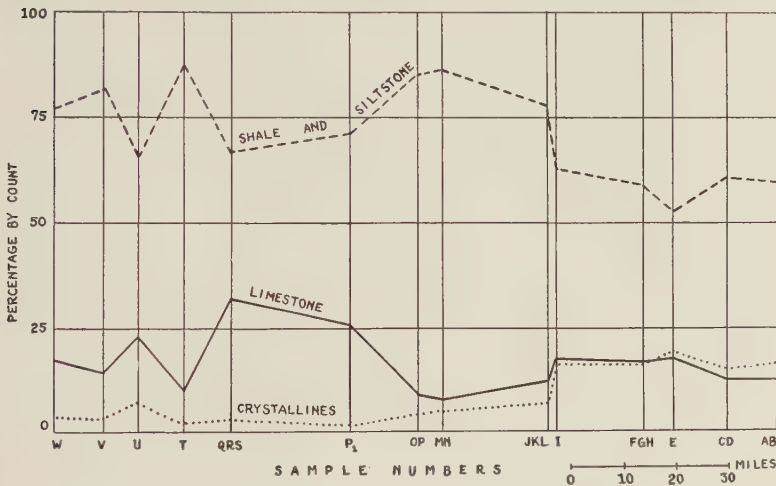


FIG. 8.—Lithology curves of north-south samples

strata. This situation seems to be reflected in the limestone curve, which shows an upward trend between samples $O-P$ and P_1 .

As further evidence of the cleavage into at least two types of till, a scatter diagram¹⁰ was made, as shown in Figure 9. The medians of

¹⁰ In preparing scatter diagrams, the samples are plotted as points, using the median as ordinate and the quartile deviation as abscissa. The centroid of each group of points is determined by taking the arithmetic average of the X - and Y -values of the points in each group. Next the mean absolute deviation of the samples from the appropriate centroid is computed by taking the sum of the absolute differences between the X -value of each point and the X -value of the centroid, and dividing by the number of points. The same procedure is followed with the Y -values. A rectangle, having sides equal to the mean deviation (or some multiple of it) is then constructed with the centroid as center. In Figure 9 the sides of the rectangles are equal to twice the mean deviations, to depict the smaller rectangle at an appreciable size.

the samples are shown as ordinates and the quartile deviations as abscissae. It will be noted that the samples in the "Southern" group are widely scattered, but the "Middle" and "Northern" groups comprise a more compact unit. There is no overlap between the "Southern" and "Middle" types, but the "Northern" merges to some extent with the "Middle," and for the purposes of the diagram they have been treated as a single group.

The centroids of the two groups of samples are shown by circles, and the deviation of the samples about these centroids is indicated

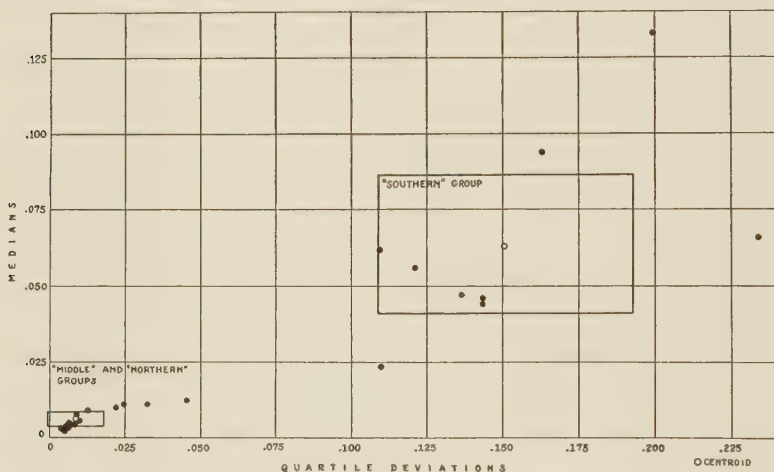


FIG. 9.—Scatter diagram of north-south samples

by the rectangles drawn with the centroids as centers. The "Southern" suite has the larger rectangle, and the samples of this group therefore depart more widely from the average composition of the set than do the other samples. Physically this concept relates to the homogeneity of the tills, since the degree of deviation from one sample to the next is a measure of how much alike they are in their composition. This relative homogeneity may be expressed quantitatively by comparing the areas of the rectangles, but as insufficient samples are involved in the present study to clothe the value with any statistical significance it is perhaps more appropriate to consider the rectangles as first approximations only.

In particular reference to the differences between the "Southern"

and the other types of till, it should be pointed out that the factors which controlled the loading of the Bloomington and later ice sheets with fine material are not clear from the samples themselves or from the field relations. The underlying bed rock can hardly be invoked, because the break in the mechanical composition occurs not at the contact between two different types of bed rock, but about 40 miles south of it in an area underlain mainly by shales and siltstones. The writer believes that the change in the textural composition must be traced to the movements of the ice after the Champaign till was deposited, and before the outer Bloomington moraine was laid. It is possible that the Champaign ice receded a considerable distance, and during its retreat locked in temporary lakes which served as sites for the deposition of silts and clays. When the ice advanced again, the inclusion of this material would profoundly affect the mechanical composition of the till.

There are numerous evidences in the Chicago area of temporary lakes formed in the wake of retreating ice sheets, and the material deposited in them would furnish sufficient silt and clay to load the ice. Whether the Champaign ice receded as far north as the Lake Michigan basin before it readvanced is not clear, but the conditions in that basin were ideally suited to the formation of such ice-locked lakes.

COMPARISON OF THE TWO SUITES OF SAMPLES

The data presented may suggest some of the differences between lateral variations along a moraine, and those that occur in the line of glacial movement. The medians of the Valparaiso till fluctuate in their absolute values, and the principal variations are due either to the assimilation of surficial materials near the ice margin, or to varying drainage conditions along the ice front. The medians of the samples in the line of glacial movement, on the other hand, reflect abrupt changes in the composition of the till as a whole. It thus seems that in the line of glacial movement the local variations do not appear to be as prominent as they are laterally along any one moraine, but the writer believes that if samples were taken from any considerable extent along each one of the moraines involved, the fluctuations of the medians would be of about the same order of magnitude as those of the Valparaiso till.

The influence of the immediately underlying bed rock on the mechanical composition appears to have been as inconsequential in one till as in the other. The pebbles in the tills along the line of glacial movement reflect the change from Silurian to Pennsylvanian more nearly at the contact than the Valparaiso till alone reflects the change from Silurian to Devonian. In general it may be said that the occurrence of pebbles of the immediately underlying bed rock in a given till is a function largely of protective coverings of the rock, and of the directions of the currents in the ice.

THE CORRELATION OF GLACIAL TILLS

Variations in the mechanical and lithological composition of tills have a bearing on the possible correlation of such deposits. The variations in the mechanical composition of the samples of any one set of till samples should be so small that the frequency-distribution graphs of the sets to be differentiated do not overlap. Such a condition exists in the case of the "Southern" and "Middle" tills along the line of glacial movement, but the "Middle" and "Northern" types overlap to some extent. Nevertheless, the overlap in the latter case, as shown by the triangle diagram and the median curves, did not include more than a single sample, although the sand and gravel contents were so closely related that certain differentiation may be doubtful.

The local variations shown by the samples of till from the Valparaiso moraine clearly indicate that it is not safe to base differentiation on a single sample. Even in the case of several samples, the field relations must be carefully investigated, because local surficial material and varying drainage conditions may greatly affect the composition of samples in a limited area. To test the effect of drainage conditions on the composition, a sample of Marseilles till was collected adjacent to a large outwash channel south of Kankakee. The composition was found to agree very closely with an average "Southern" type sample, and if differentiation had been based on such a random sample, an error of considerable magnitude would have been involved. It is necessary, therefore, that a sufficient number of samples be analyzed, to obtain the average composition of the till. By comparing *suites* of samples, the accidental variations due to drainage at the ice margin, or to the effects of local surficial mate-

rials, may be largely eliminated. The net effect will be the comparison of *sets* of data, and the differences among the sets, expressed as triangle diagrams, scatter diagrams, or the like, will form the basis of the differentiation. Once the cleavage into two types has been effected, it may fairly reasonably be predicted that a given sample of one or the other of the tills will fall within the category to which it belongs.

The pebble counts made in the present study did not reflect the changes among the tills as clearly as did the mechanical analyses. It is conceivable that the proportion of different rock types among the erratic pebbles may have shown some differences if investigated. Studies of the heavy minerals in some grade sizes were made, however, especially of the samples on both sides of the prominent break at Danville. The heavy minerals were separated from samples *I* and *J* by bromoform in the $\frac{1}{4}$ - $\frac{1}{8}$ and $\frac{1}{8}$ - $\frac{1}{16}$ mm. grades, and 1000 grains in each slide were counted. No outstanding differences were noted either in the two grades studied, or in the two samples. In both cases about 25 minerals were present. The predominant ones were hornblende, the iron ores, and garnet. The hornblende varied from 22 to 36 per cent, the ores from 20 to 31 per cent, and garnet from 10 to 13 per cent. Epidote, tourmaline, and hypersthene varied from less than 1 per cent up to several per cent, and all the others, among them actinolite, augite, muscovite, staurolite, rutile, titanite, zircon, and zoisite, were present from traces up to nearly 1 per cent. These counts were based on the acid-insoluble residues of the grades, so that neither calcite nor apatite were present.

Additional studies of the heavy minerals in other samples in the line of glacial movement were made, but in no case among the minerals was noted a variation greater than similar variations among other samples. The absence of any striking changes in the heavy minerals of these grades suggests that the "Southern" and "Middle" tills are closely related, and this appears to strengthen the hypothesis that the "Middle" till resulted from the loading, in the manner suggested above, of the earlier till with silt and clay. Such additions to the finer ranges would not greatly affect the mineralogical composition of the sand sizes, but they would affect the mechanical composition of the till as a whole.

DETERMINATION OF THE THICKNESS OF THE BLOOMINGTON DRIFT

The sharp break in the mechanical composition of the two tills at Danville suggested the possibility of applying mechanical analysis to a typical differentiation problem. It seemed likely that beneath the Bloomington moraine there should be a considerable deposit of earlier Wisconsin drift, and it should be possible to determine the thickness of the Bloomington drift from a series of samples taken vertically. Samples were therefore collected along a new hard road on the west side of Lake Vermilion, northwest of Danville. Lake Vermilion is an artificial lake, dammed in the valley of the north fork of Vermilion River. Its altitude is approximately 575 feet, and its surface lies some 155 feet below the crest of the moraine in this general locality.

The sampling locality is immediately adjacent to the point from which sample *K* in Figure 1 was taken. The road crosses a small inlet of the lake, and rises to the north. Road cuts and small lake bluffs afforded an opportunity for collecting samples at vertical intervals of 5 feet through a total range of more than 60 feet. Twelve samples were collected within a distance of a quarter mile, only one by the use of a soil auger. The samples were numbered from the bottom up, the lake level sample being 0. Megascopic examination showed no striking changes among these samples.

Alternate samples were analyzed, to obtain some idea of the altitude of the break in composition. It was found that the change in composition occurred between samples 8 and 9, at 40 and 45 feet above the lake. To verify this, several lower samples were analyzed, and all of them showed the typical "Southern" composition. These are samples 2, 4, 5, 6, 7, and 8. Above the break, samples 9 and 11 were analyzed, and both showed the typical "Middle" composition. Figure 10 includes both the cumulative curves and a triangle diagram of the samples. In addition, sample *K* of the main set is included to indicate the composition of a sample from near the top of the moraine in this vicinity. It will be noted that the cumulative curves and the points in the triangle diagram separate into two groups between which there is no overlap. The dashed lines in the triangle diagram indicate the areas occupied by the till types in Figure 6.

The top of the pre-Bloomington drift has accordingly been placed

between 40 and 45 feet above Lake Vermilion. This is at an altitude of 615-620 feet, and since the Bloomington moraine rises to 730 feet, there are 110-115 feet of Bloomington drift present. The altitude of the Bloomington outwash plain in front of the moraine is from 640 to 650 feet. This altitude is from 20 to 40 feet above the contact of the tills, and if no erosion of the earlier Wisconsin drift by the Bloomington ice is assumed, the outwash of the Bloomington moraine ranges from 20 to 40 feet in thickness.

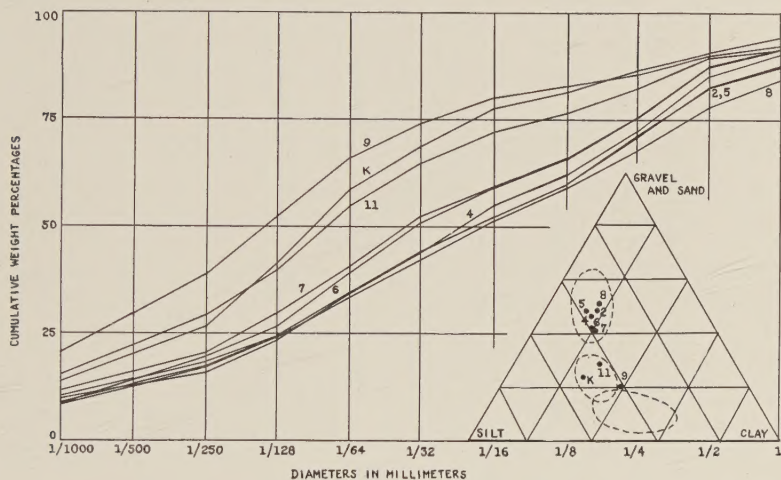


FIG. 10.—Cumulative curves and triangle diagram of samples for determining the thickness of the Bloomington drift.

SUMMARY

The present study has shown that till is perhaps not so heterogeneous as had heretofore been supposed, but that a given ice sheet tends to produce till having a fairly well-defined frequency distribution. This more or less homogeneous basic composition is modified locally by drainage conditions at the ice margin, and by the incorporation of unconsolidated deposits beneath the edge of the ice.

The ultimate source of the material comprising till is, of course, the terrane over which the ice moved, but the proportionate contributions made by the bed rock and by overridden surficial deposits are difficult to evaluate. The data from the Valparaiso moraine have clearly shown that the immediately underlying bed rock was not

necessarily related either to the pebbles in the till or to the mechanical composition. The clayey nature of the Valparaiso moraine is generally attributed to the Devonian shales in that region, and the presence of numerous Sporangites is an indication that some contribution has certainly been made. It is strange, however, that the mechanical composition does not reflect the change in the pebbles near Joliet, by being coarser to the west, where limestone pebbles predominate over shale and siltstone.

The present study has also shown that mechanical composition may be used as a means for differentiating tills under certain favorable conditions. Where these conditions prevail, as they do at Danville, differentiation is possible even in the absence of megascopically visible differences, or the presence of weathered zones.¹¹

¹¹ The writer wishes to acknowledge the helpful suggestions and criticisms of Professors J. H. Bretz, A. Johannsen, and F. J. Pettijohn of the Department of Geology of the University of Chicago. He is also indebted to Dr. M. M. Leighton, Chief of the Illinois State Geological Survey, who aided considerably in the development of the study.

